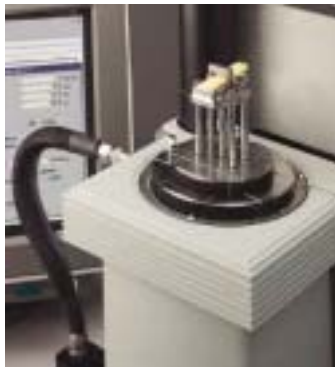
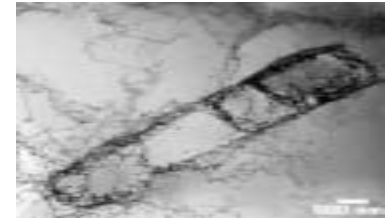
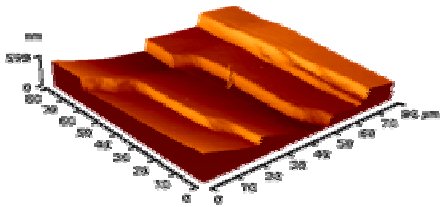


# Opportunities for X-ray Imaging of Plastically Deformed Metals

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Workshop on Emerging Scientific  
Opportunities Using X-ray Imaging  
The Abbey, Lake Geneva, Wisconsin  
August 31, 2004

# Outline

1. Overview of economic drivers
2. Description of industrial problem
3. Underlying processes of plastic deformation
4. What are the important experimental questions?
5. Conclusions

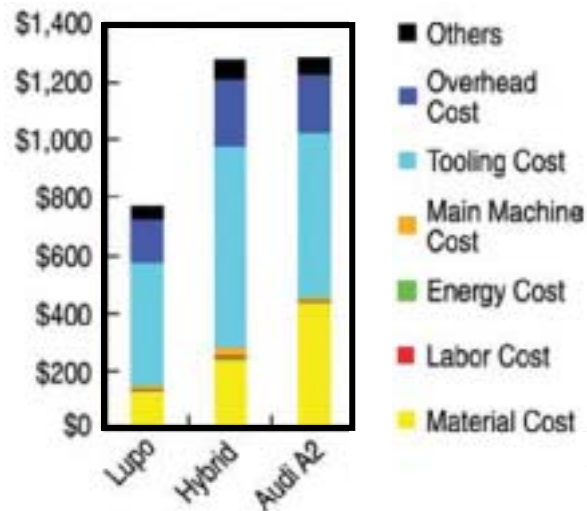
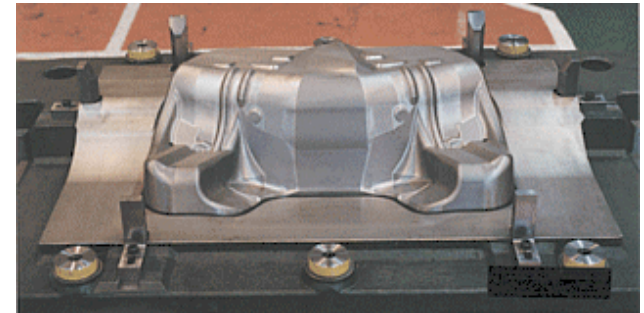
# Metal Forming / Automotive Manufacturing

**Size of U.S. Metal Forming Industry:**

**Value added / year > \$20 Billion**

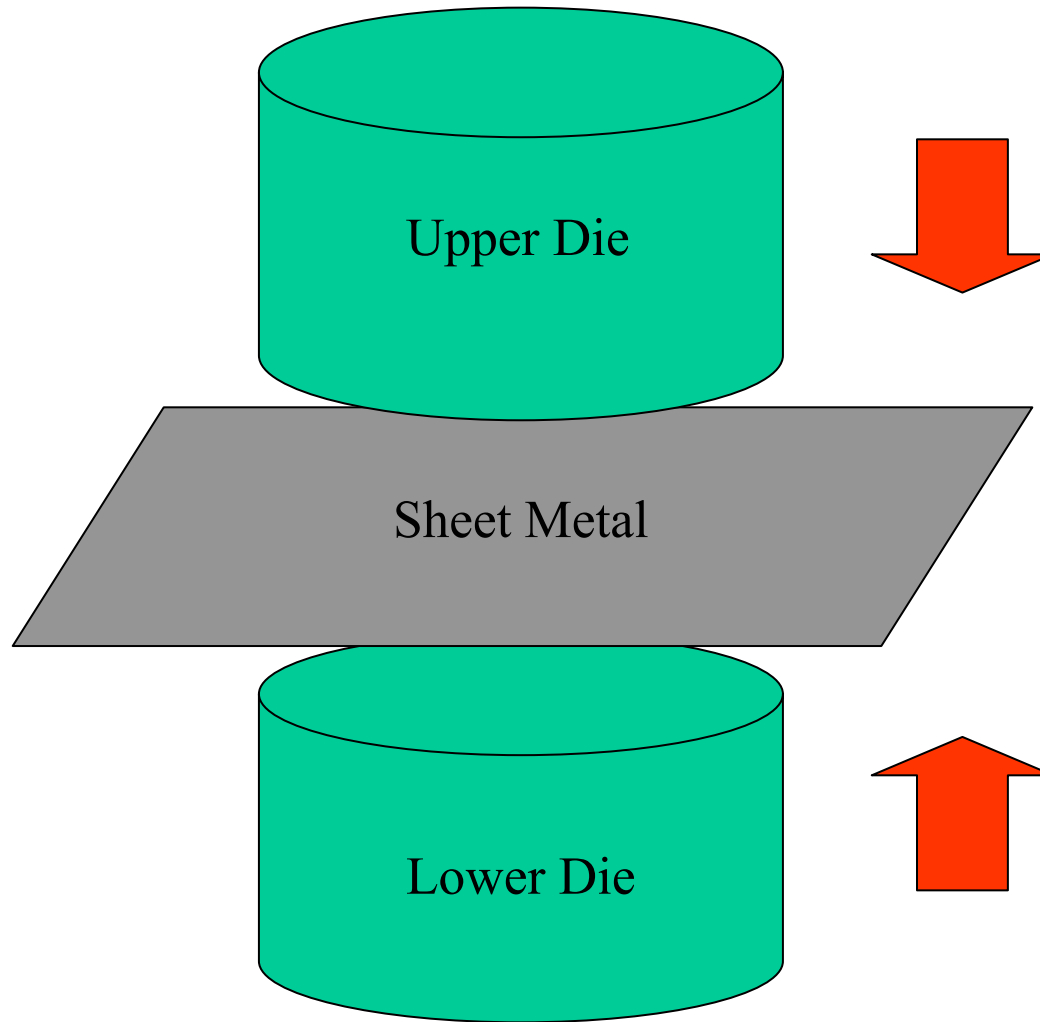
**Largest User: Automotive Industry**

Approximately 1/3 of the weight of a car is formed metal products.

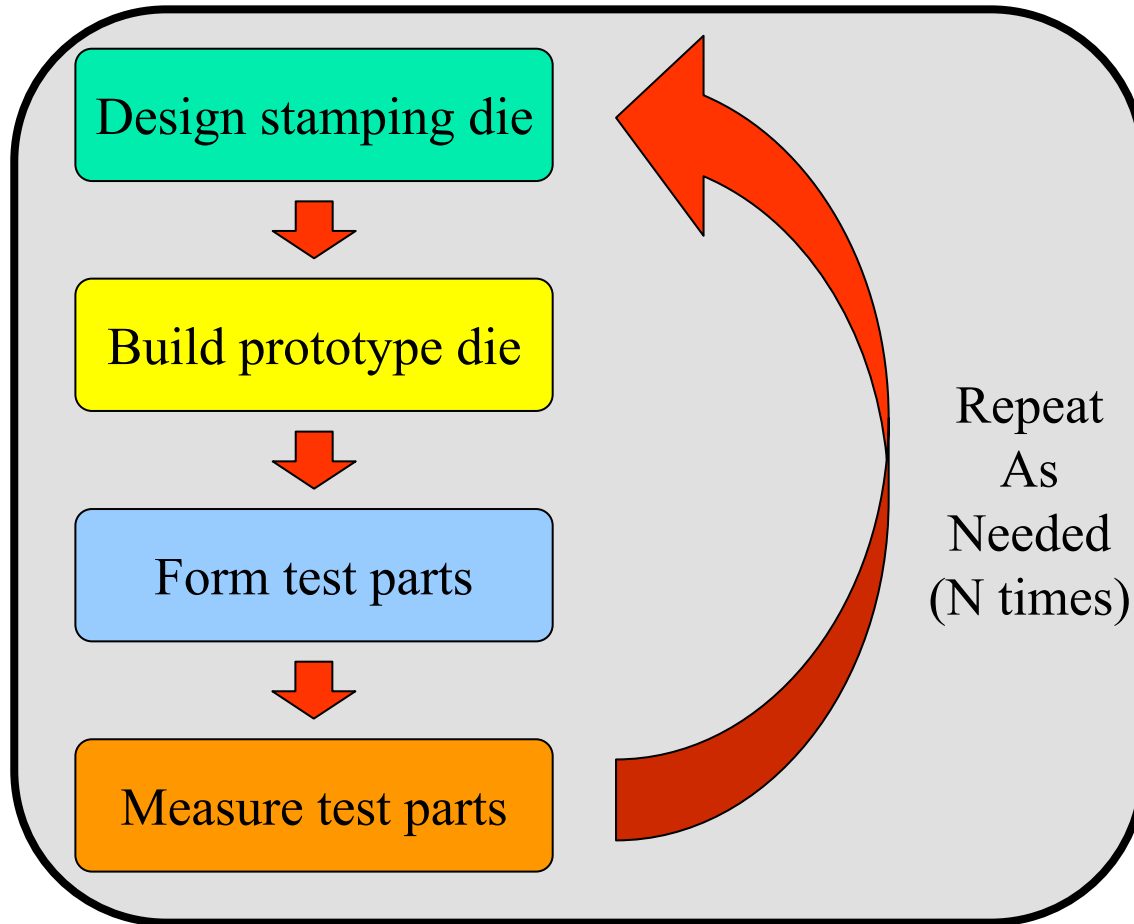


Part cost breakdown for small cars.  
This doesn't include assembly costs.  
(Kelkar *et al.*, J. of Metals,  
pp 28-32, Aug 2001)

# Why so expensive???



# Why so expensive???



Repeat  
As  
Needed  
(N times)

For mild steel,  
 $\langle N \rangle \approx 12$

For HSS or Al alloys,  
 $\langle N \rangle \gg 12$

# Why so many repeats?

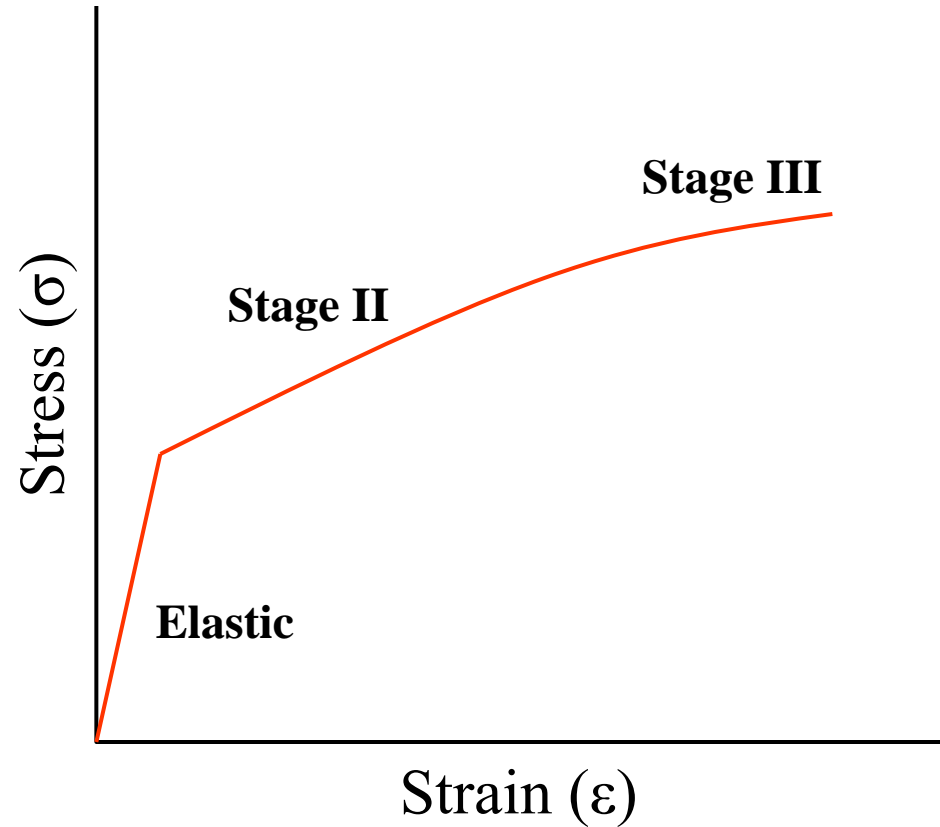
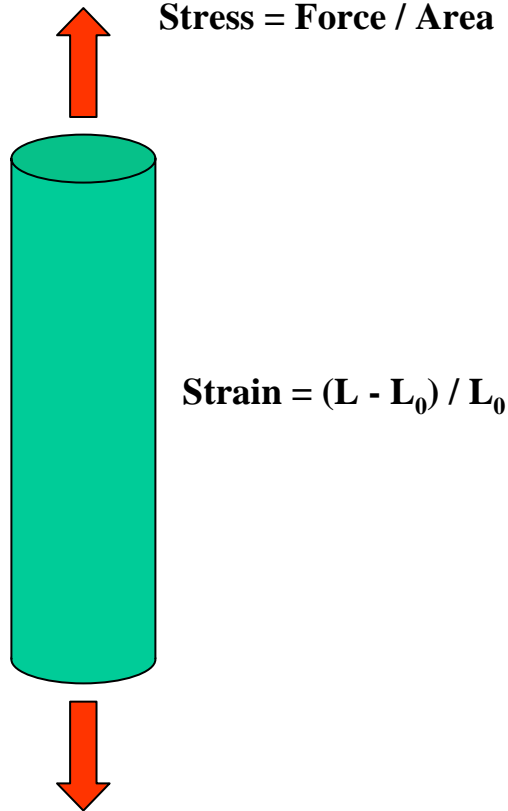
Mechanical behavior changes  
**dramatically**  
during deformation.

Empirical solutions have been  
**intensively**  
explored for decades.

Fundamental solutions have been  
**intensively**  
explored for decades.

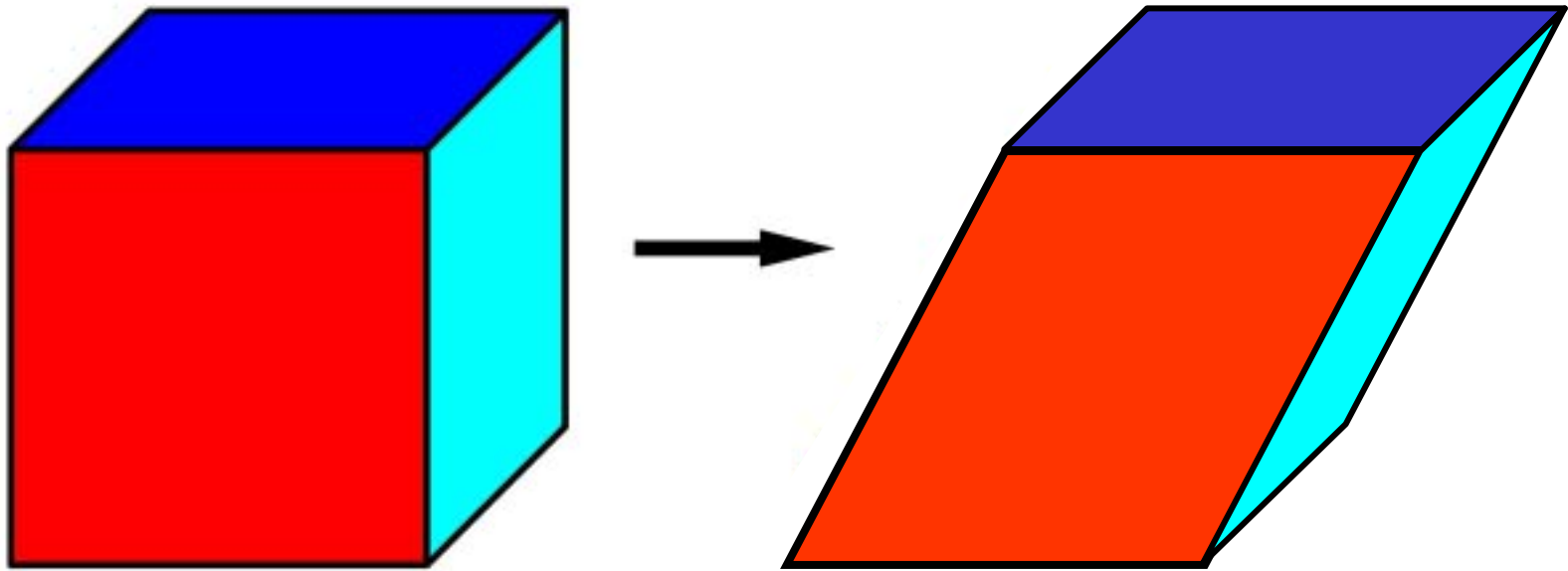
This is not an easy problem...

# Generic Single-Crystal Work Hardening Curve



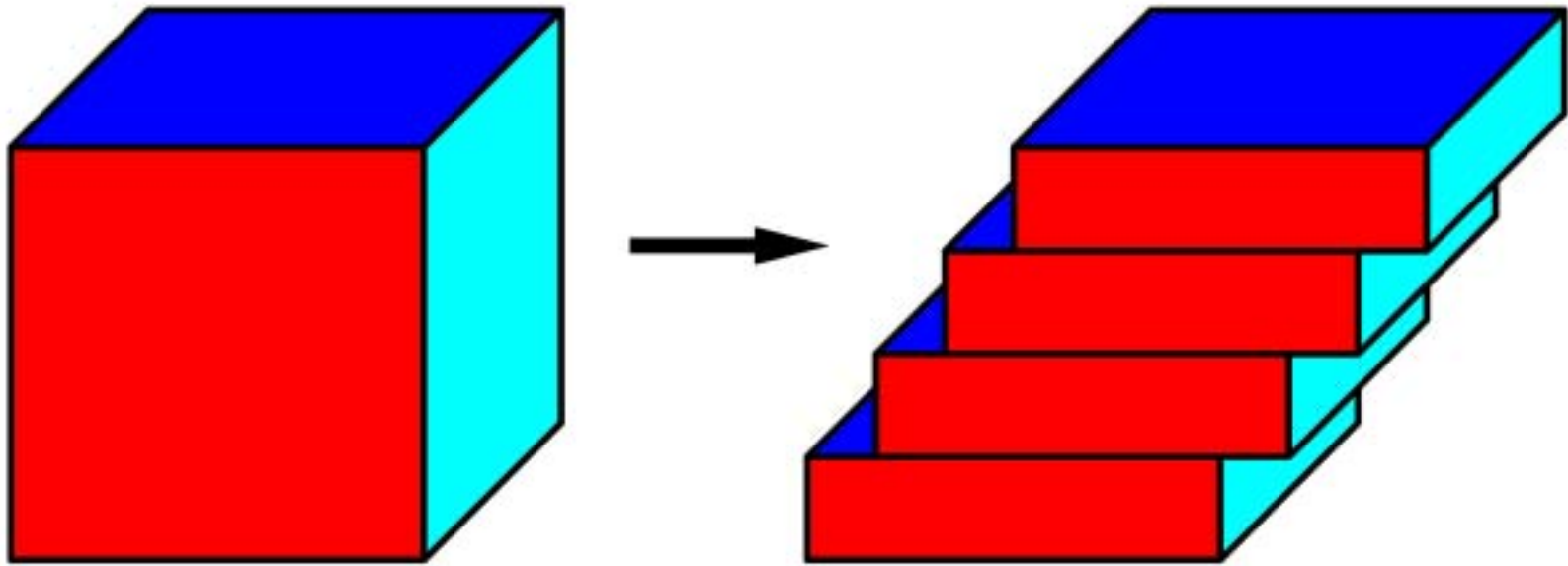
**Details depend upon:** Material, Temperature, Strain Rate, Tensile Axis, Strain History, Microstructure, etc...

# Deformation by Slip



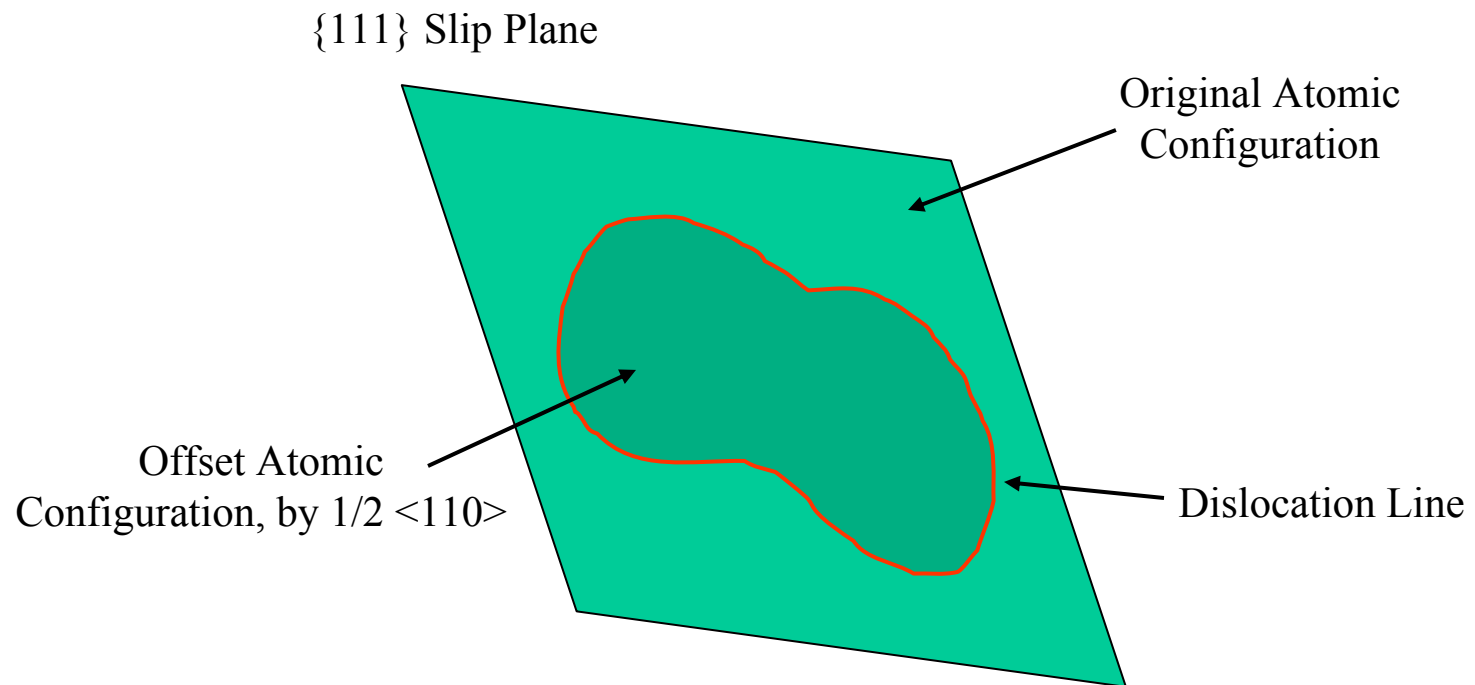


# Deformation by Slip



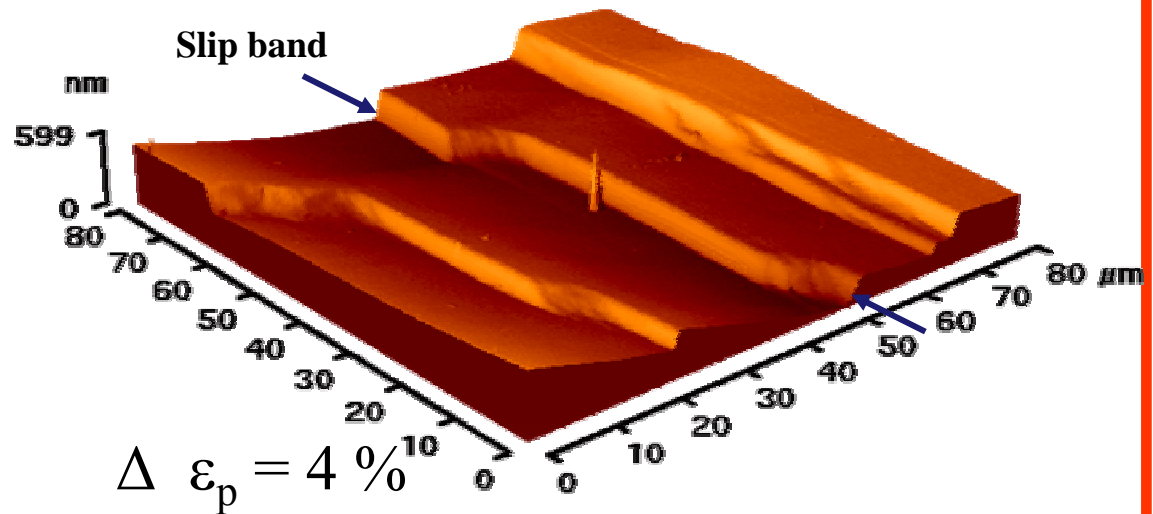
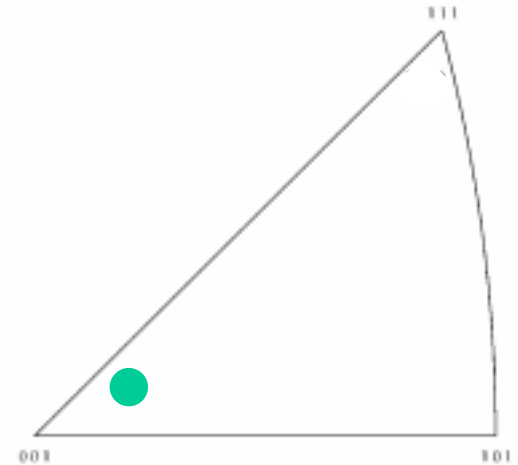
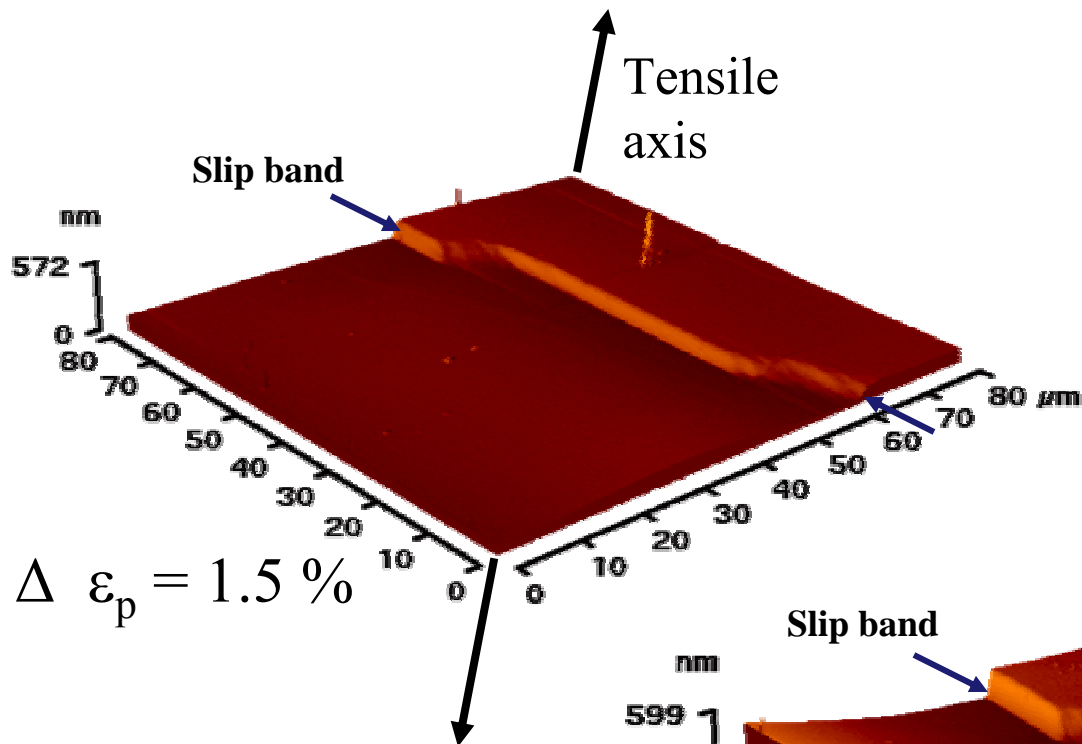
For fcc metals, slip planes are  $\{111\}$  and the slip directions on these planes (Burgers vectors) are  $\frac{1}{2} \langle 110 \rangle$

# Dislocation Loop on Slip Plane



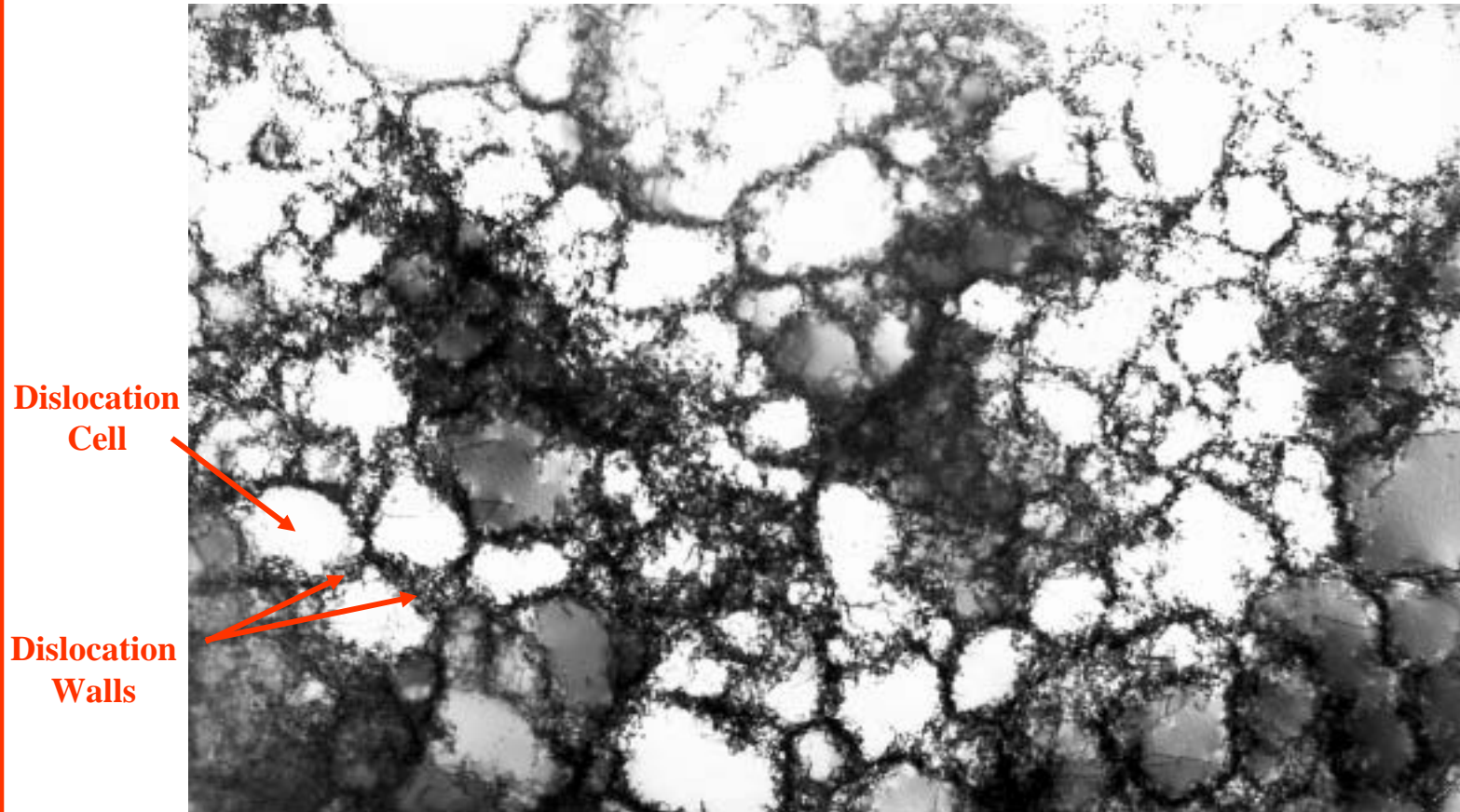
**A dislocation cannot terminate within the bulk.  
It either forms a loop or terminates on a surface  
(external, precipitate, grain boundary, etc...).**

# Near <001>, Atomic Force Microscopy



# Dislocation Cell Structure

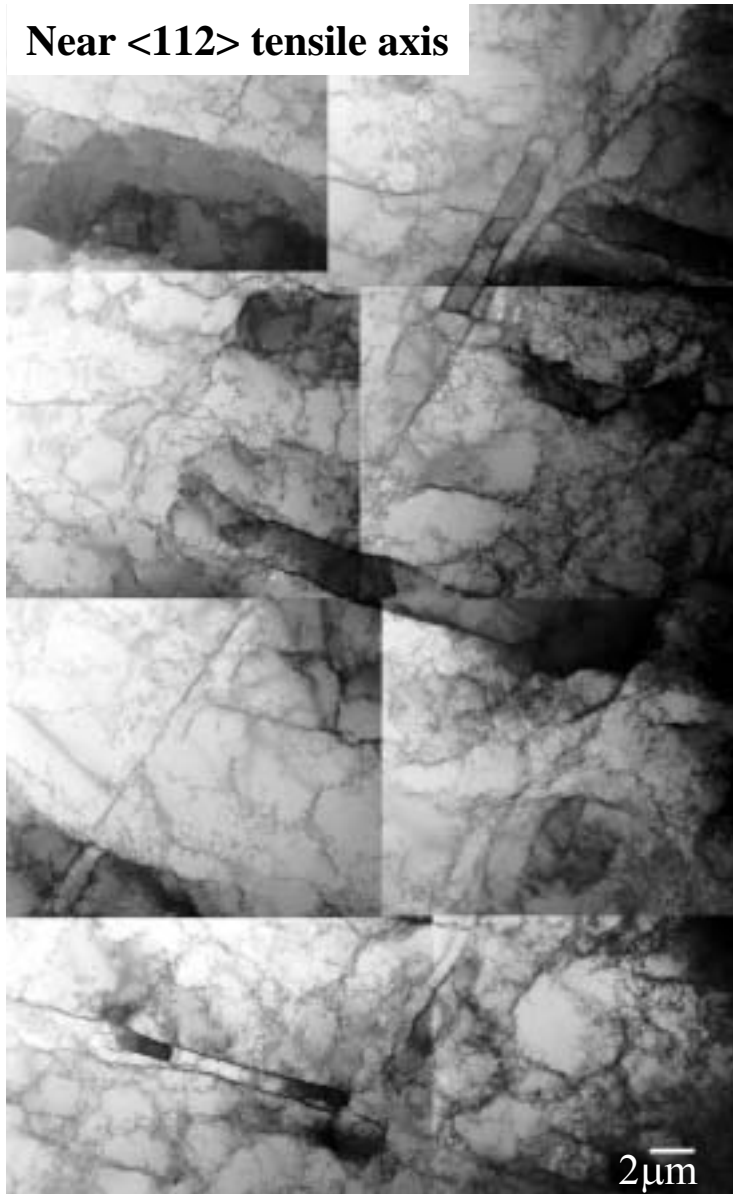
Cu Single Crystal,  $\langle 100 \rangle$  Tensile Axis, Stage III



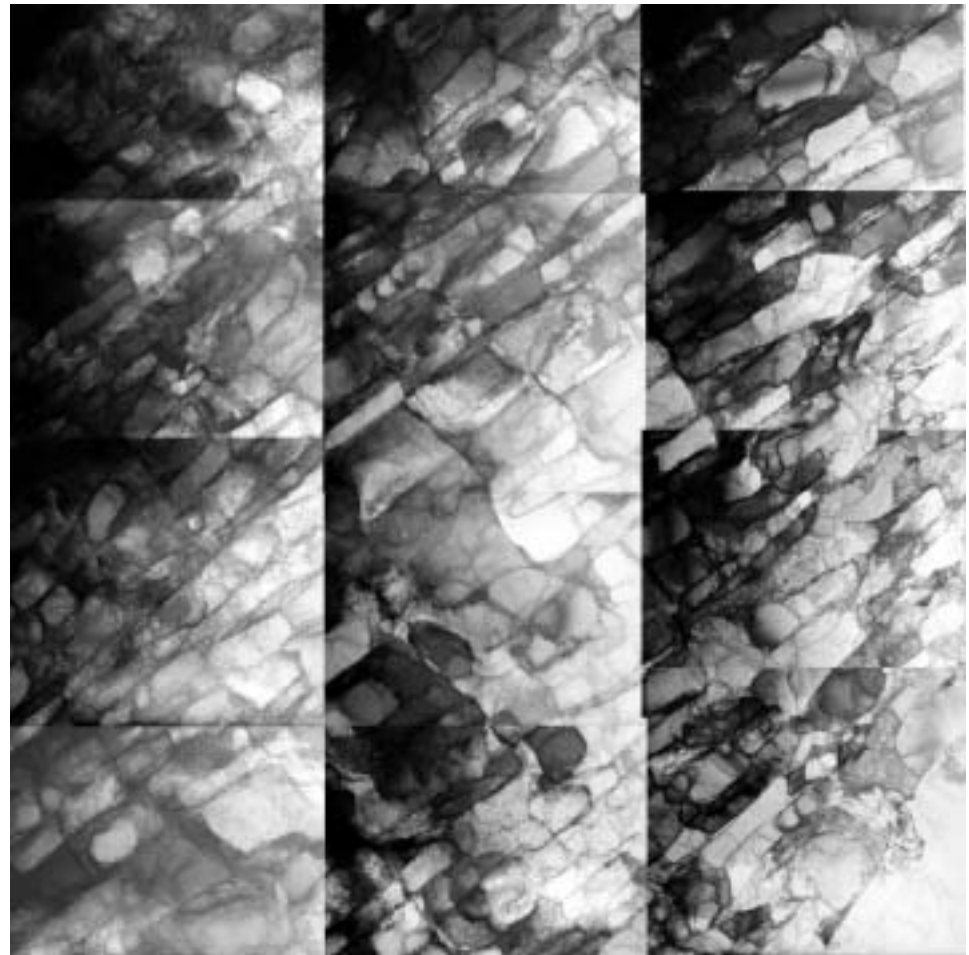
Micrograph Courtesy of H. Mughrabi, unpublished

# Dislocation Cell Structure

Near  $\langle 112 \rangle$  tensile axis



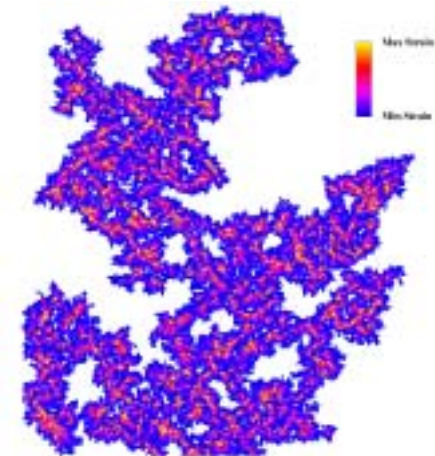
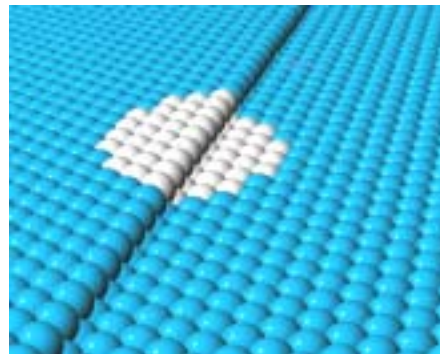
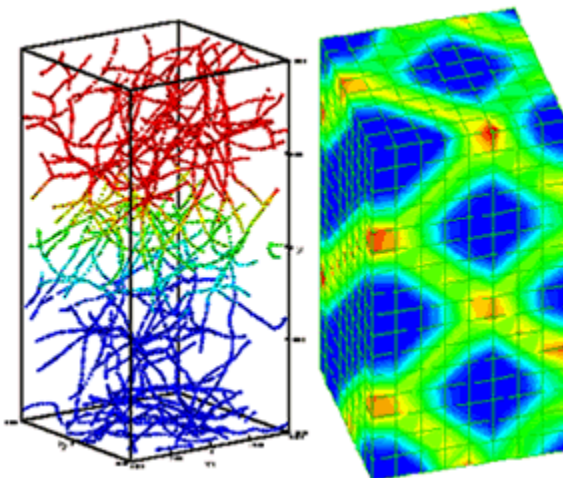
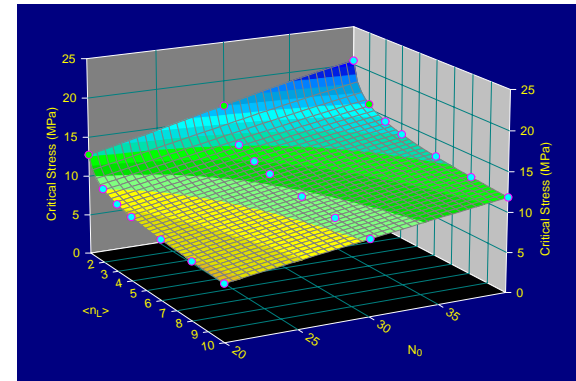
Near  $\langle 111 \rangle$  tensile axis





# Theory and Modeling Approaches Used

1. Statistical physics
2. Non-linear dynamics
3. Strain gradient theory
4. 3D dislocation dynamics
5. Atomistics using classical potentials (primarily EAM)
6. Atomistics using DFT and DFT-derived n-body terms



# What are the important features???

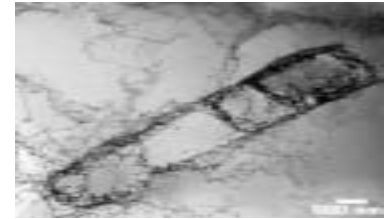
## General Notes:

- *In situ* data strongly preferred
- Dislocations are attracted to surfaces, need samples *at least* 100  $\mu\text{m}$  thick.

## Information needed on the evolution of the:

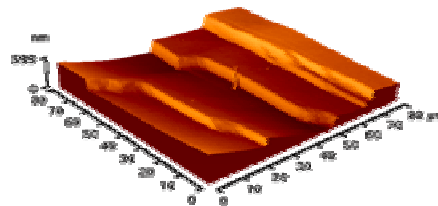
### Sample bulk

- spatial distribution of dislocation walls
- dislocation density of the walls
- angular misorientation across the walls
- total and local dislocation line length for the various slip systems
- local stresses in sample (much better than 1  $\mu\text{m}$  resolution!)



### Sample surface

- slip line and slip band surface structure with good time resolution (ms)



# Conclusions

- Deformation of metals is a **VERY BIG INDUSTRY**.
- Industrial costs are huge due to inadequate understanding.
- Deformation of metals is very complex.
- **We need help !**
- Existing data inadequate for current modeling and theory needs.
- We don't know how to measure everything needed.

